AN EXAMINATION ON SMOKE CONTROL BY MEANS OF NUMERICAL SIMULATION IN A LONG URBAN TUNNEL (THE YAMATOGAWA TUNNEL)

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ABSTRACT

The Yamatogawa Tunnel, which is currently under construction, is an urban tunnel on the Hanshin Expressway. The Yamatogawa route is about 9.7km in length, of which 6766m is tunnel and 1541m is lidded - trench structure. The tunnel consists of three tunnel parts. The longest one is about 5km in length, including a junction.

The ventilation strategy for the Yamatogawa Tunnel adopts the longitudinal ventilation method.

In the event of a fire in the tunnel during a congested traffic condition, the velocity of the longitudinal air-flow in the vicinity of the fire point is designed to be kept as close as possible to 0m/s, to secure several minutes for escaping from the fire point. This ventilation control method is called "velocity of the wind of a fire point shifts 0m/s"(VWFS-0).

In this study, numerical simulation was conducted to analyze how smoke and hot gases would propagate in this tunnel during the emergency ventilation operation. The scale of maximum heat release rate was assumed to be 30MW, and the velocities of the longitudinal air-flow changing with time would be controlled in order to achieve VWFS-0.

Consequently, the relation between the smoke diffusion and the evacuation distance by the difference of longitudinal gradient was obtained. Based on these results, the intervals of the emergency exits were determined.

1. INTRODUCTION

The Yamatogawa Tunnel consists of three tunnels (tentatively- named as Tunnels A, B and C in this paper) connected by a specific lidded - trench structure. The longitudinal ventilation method is adopted in all of the three tunnels. An outline of the ventilation is shown in Figure1.

Tunnel ventilation is required not only to maintain visibility inside the tunnels but also to protect environment in the inhabited area near the tunnel portals, during normal operation. The air inside the tunnels is assisted to flow to the ventilation stations located in the tunnels by operating

longitudinal jet-fans, and then is exhausted high up in the sky via the shafts where SPM (Suspended Particulate Matter) is removed.

The operations of the ventilation systems are varied depending on whether the traffic condition is free – flow or congested. In free – flow conditions, it is usually assumed that the traffic behind the fire will come to a stop and the traffic ahead of the fire can leave the tunnel. As shown in Figure2 (a) , in order to provide safe environment for tunnel users, the jet-fans are operated to force the smoke and hot gases downward not to propagate upward from the fire point. In congested conditions, it is usually assumed that the traffic on both sides of the fire point will come to a stop. As shown in Figure2 (b), for providing a safe environment in the both directions, avoiding de-stratification of the smoke layer is crucial. Therefore, in order to mitigate the effect of the longitudinal air-flow (including that induced by traffic force), the jet-fans are operated to lower the longitudinal velocity (aiming at reducing its value to 0m/s) inside the tunnel at an early stage.

In this study, the smoke behavior under an emergency ventilation control was obtained by the numerical simulation, and the evacuation environment was discussed. Only Tunnel C (westbound) under congested traffic conditions was taken up in this study, since it would be longest among the three tunnels and the ventilation control would be considered to be complicated. Tunnels under free-flow conditions were not addressed here, since there was a lot of knowledge in the previous studies [1], in which ensuring the velocity that could avoid backlayering of the smoke provided the safe evacuation environment to the tunnel users.

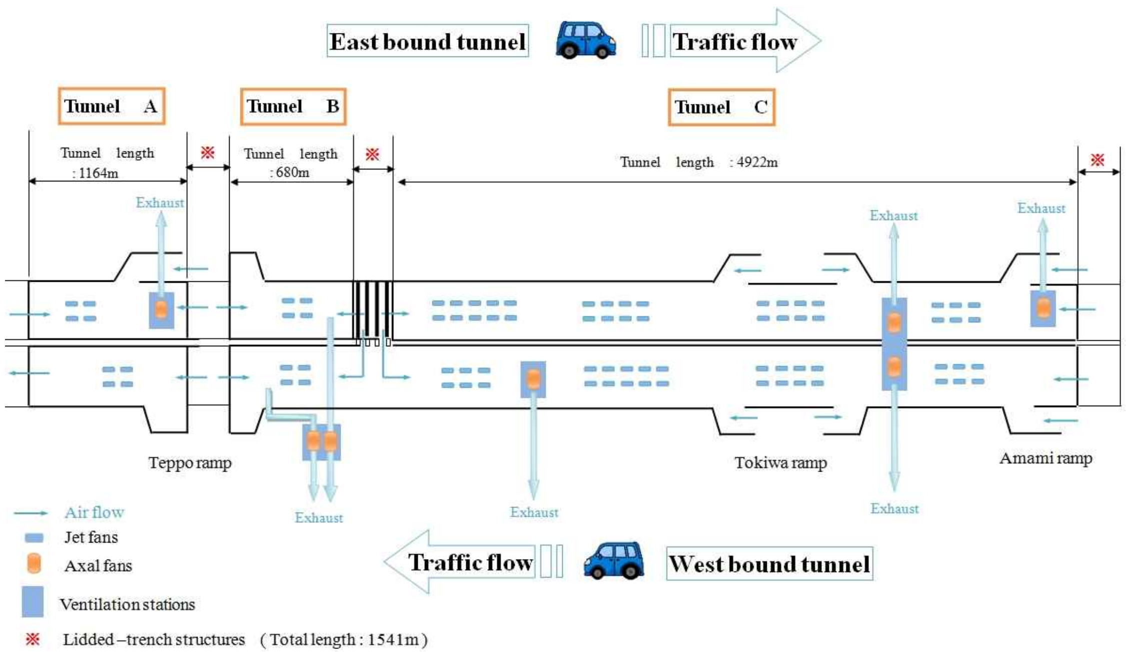


Figure 1 Ventilation strategy for the Yamatogawa Tunnel

(a) Free-flow traffic condition

(b) Congested traffic condition

Figure 2 Emergency ventilation controls

2. CONDITIONS AND APPROACH

2-1 Structural conditions and examined points of the tunnel

As shown in Figure3, the cross - sectional area inside of Tunnel C which is shield structure is 74m^2. As shown in the longitudinal sectional view (Figure4), the vertical gradient of the tunnel varies complexly. The behavior of the smoke is expected to be different according to the gradient. In this study, we examined three cases (0.3%, 2% and 3% gradient) which are typical gradients of Tunnel C.

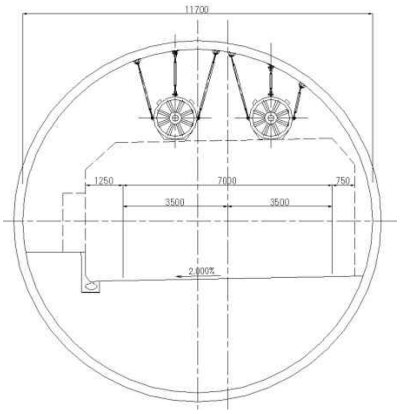


Figure3 Cross-section of Tunnel C

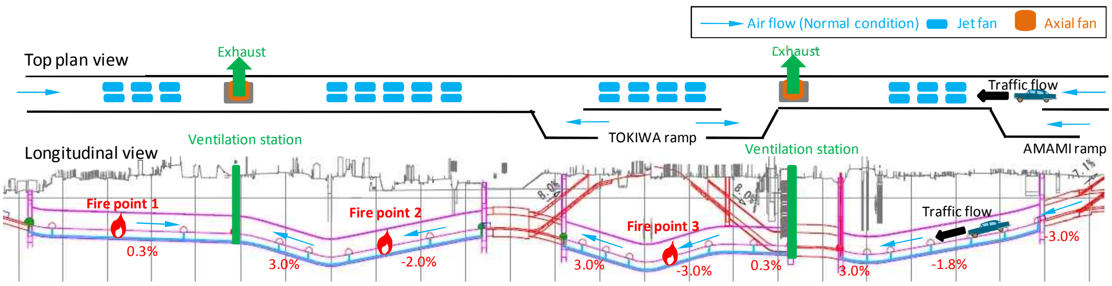


Figure4 Longitudinal sectional view and examined places in Tunnel C (westbound).

2-2 Ventilation operation in case of a fire

In congested traffic, it is thought that the longitudinal air-flow velocity inside the tunnel is easily controlled to be 0m/s at the fire point, since the traffic force is small and the velocity is low. However, when a fire occurs in the early stage of the congested traffic, high longitudinal air-flow velocity remains due to large traffic force. If the longitudinal air-flow velocity is not controlled to be 0m/s at the fire point during the earliest stage, de-stratification of the smoke will causes worsening the evacuation environment. Hence, in this study, the latter scenario was selected, assuming the worst case.

Figure 5 shows the time-sequence diagram from the occurrence of the accident to the commencement of the ventilation control. The fire was assumed to begin at time equal to zero (t=0s). A cessation of traffic flow occurred at 250 seconds before the occurrence of the fire due to some reasons, the traffic accident occurred at 60 seconds before the fire, and then the fire occurred by, for example, an overheated engine or a collision at 0 seconds. It took 120 seconds to detect the fire and to start the ventilation control. Activating the jet-fans in the vicinity of the fire point might cause de-stratification of the smoke and hot gases, and might result in worsening the evacuation environment. Therefore, the jet-fans more than 500m away from the fire point were activated to control the longitudinal air-flow.

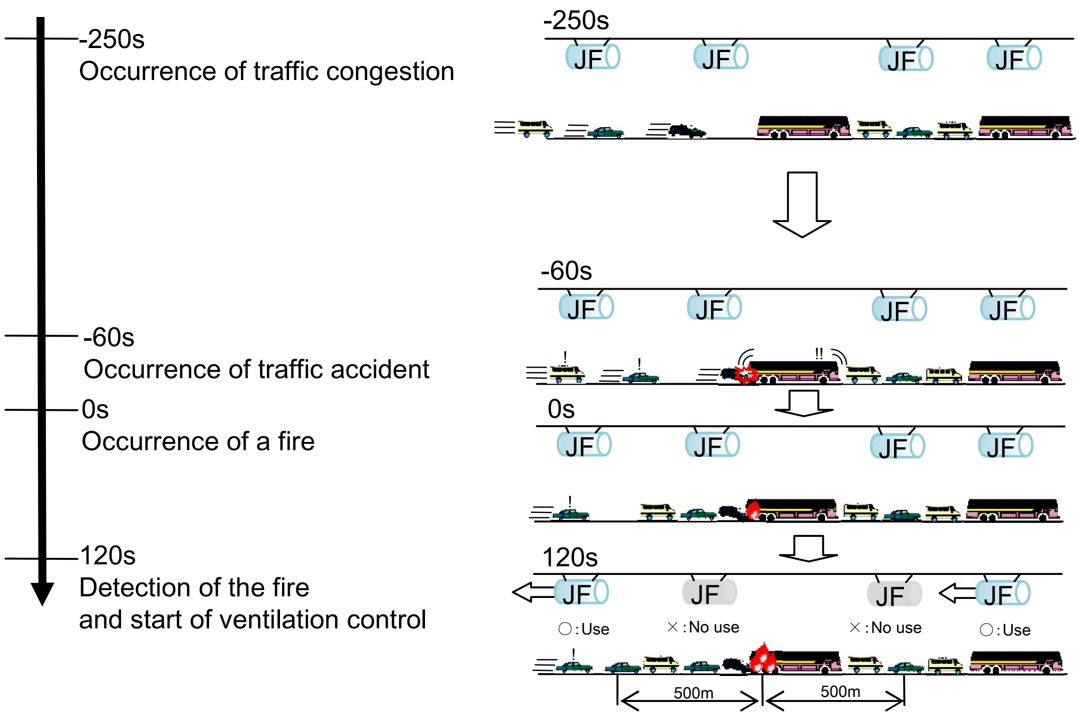


Figure5 The time-sequence diagram from the occurrence of traffic congestion to the commencement of ventilation control, and the policy of ventilation control.

2-3 Assumed fire scale

A large majority of tunnel fires in Japan is caused by a single accident. In this examination, we chose a bus fire as a designed - fire scenario, since it was considered to be the maximum fire size

among the single accidents.

There were two large-scale fire tests carried out with buses. The Heat Release Rate (HRR) of the bus fire was investigated in the EUREKA EU499 – FIRETUN test series [2], and in the Shimizu No.3 tunnel fire test series [3]. Each HRR curve is shown in Figure6. It was reported in both tests that the HRR increased slowly for the first 3~5 minutes after the fire started, and then it reached rapidly a peak of approximately 30MW. In this examination, the HRR was decided in reference to a school bus fire test in the EUREKA EU499.

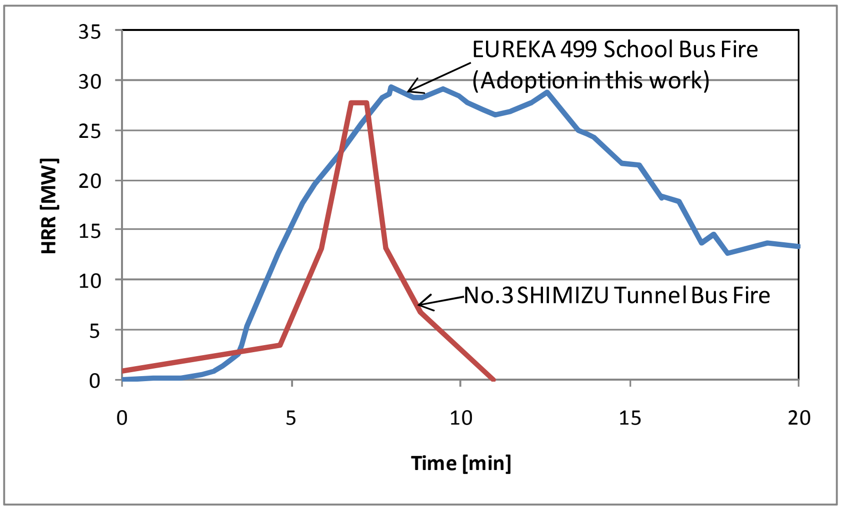


Figure6 Heat Release Rate Curve

2-4 Evaluation of the Evacuation Condition

We adopted an optical smoke density as an evaluation of the evacuation condition, as it was thought that the visibility significantly effected on evacuation activities of the tunnel users in the early stage of the tunnel fire. In road tunnels in Japan, the limit value of extinction coefficient (Cs [1/m]) that can secure the tunnel user's visibilities is generally set to be Cs=0.4 1/m. Then, in this examination, when the value of Cs at a height of a tunnel user's eyeline (assuming h=1.5m) was less than 0.4 1/m, we evaluated that this evacuation condition was safe (See Figure 7 below).

Furthermore, the time at which it is possible to start an evacuation from the fire point was assumed to be 4 minutes after the occurrence of a fire, in consideration of time for passengers getting off the bus which came to a stop in the vicinity of the fire point. The evacuation speed was assumed to be 1.0 m/s, a comparatively slow walking speed. Detailed ideas concerning the evacuation were described in a literature [4].

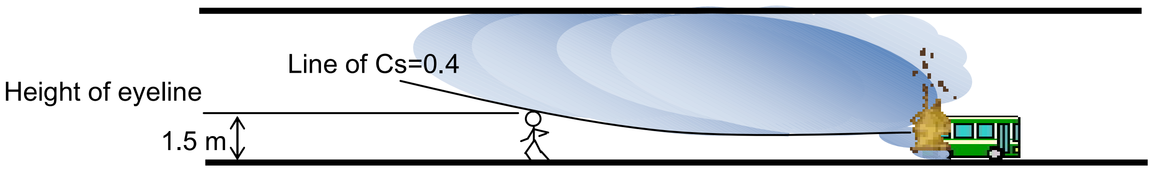


Figure 7 Evaluation of the Evacuation Condition

3. EXAMINATION PROCEDURE

In this examination, the evacuation conditions are examined by three-dimensional (3-D) fire simulation. It is not efficient to treat the whole tunnel, due to a restriction of the computational ability. Then the tunnel areas only near the fire point were analyzed in this examination. The velocities of longitudinal air-flow during the emergency control, which were obtained by one-dimensional (1-D) ventilation simulation in order to achieve VWFS-0, were adapted to velocity - boundary conditions of the 3-D fire simulation. The procedure of the examination is shown Figure8.

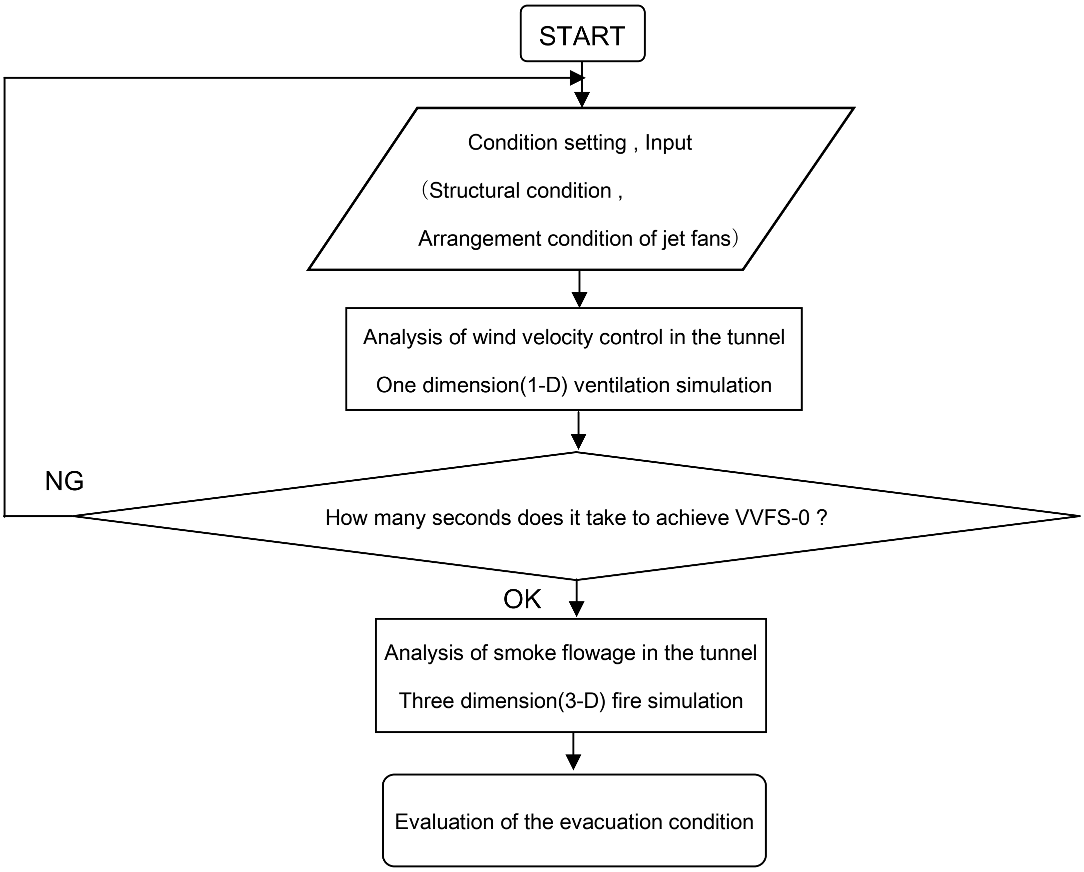


Figure 8 Examination procedure

4. EMERGENCY VENTILATION SIMULATION ON THE YAMATOGAWA TUNNEL

4-1 Outline of Ventilation Simulation

Tunnel C examined in this study, which is an urban tunnel connected with a number of ramps, has a complex ventilation system. To evaluate the dynamic behavior of this complex ventilation system, a network model using a graph expression was adopted for the 1-D ventilation simulation [5]. A traffic model (micro traffic model) considered the movement of an individual vehicle was adopted for the 1-D ventilation simulation, in order to reproduce complex traffic force induced by incoming and outgoing

vehicles through the ramps. Figure 9 shows the graph expression of Tunnel C. The symbols ○ and → in the figure show a node and a link respectively. The node shows a change in such as cross-section, junction and friction loss. The link shows a flow -transmission between the nodes.

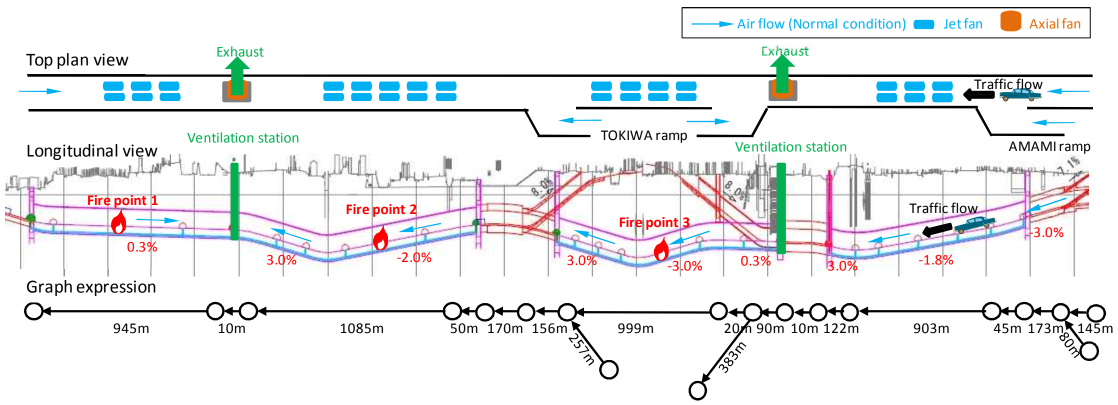


Figure 9 Representation of Nodes and Links(Tunnel C ,westbound)

4-2 Results of the 1-D Ventilation Simulation

Figure10 shows the ventilation simulation results at each fire point. Here, the longitudinal air-flow of the same direction as the traffic-flow goes in positive direction.

The direction of the longitudinal air-flow velocity in each case before the emergency ventilation control shows the same as → in Figure9. However, as soon as the congested-traffic occurs (at t=-250s), traffic force drastically decreases. Therefore, the longitudinal air-flow velocities at Fire point 2 and Fire point 3 where the normal ventilation operation is activated in the same direction as the traffic-flow, is decreasing, whereas the negative longitudinal air-flow velocity at Fire point 1 where the operation is activated in a direction opposite to the traffic-flow is increasing. Especially, the longitudinal air-flow velocity at Fire point 3 is greatly decreasing, since the fire point is very close to the ramp where the traffic force is greatly decreasing. As shown in Figure 10, when the ventilation control is changed in the emergency mode after the detection of the fire and the VWFS-0 is activated, the longitudinal air-flow velocity is going to decrease and get close to 0 m/s. it is found that the VWFS-0 has been achieved at 180 seconds from the occurrence of the fire (within 1 minute after the onset of the emergency ventilation operation). In case of a vehicle fire, the fire is slowly developing during the initial period as shown in the HRR curve (Figure 6). Therefore, until the period when the stratified smoke and hot gases are developing (after 3 minutes from the occurrence of the fire), the longitudinal air-flow velocity at the fire point inside the tunnel can be mitigated and controlled to get close to 0 m/s, avoiding the de-stratification of the smoke and hot gases, which worsens the evacuation environment.

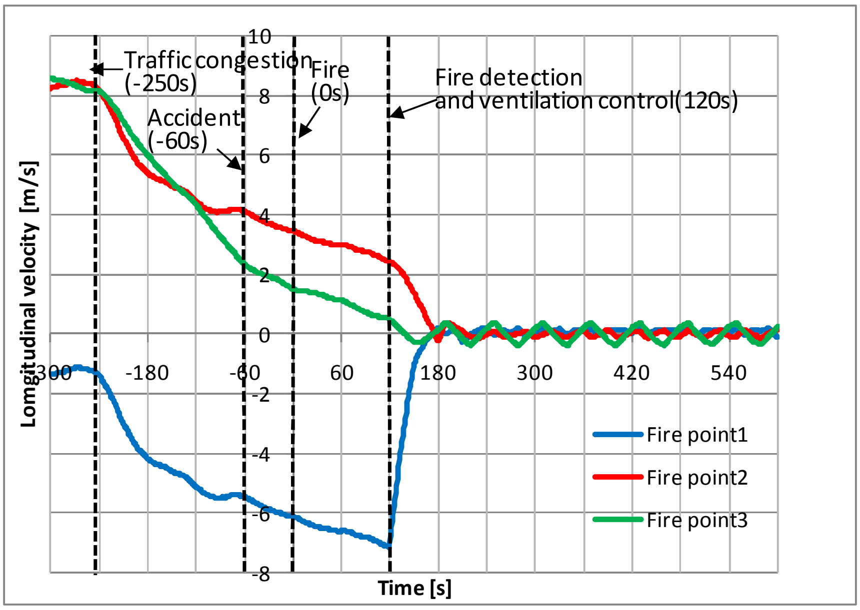
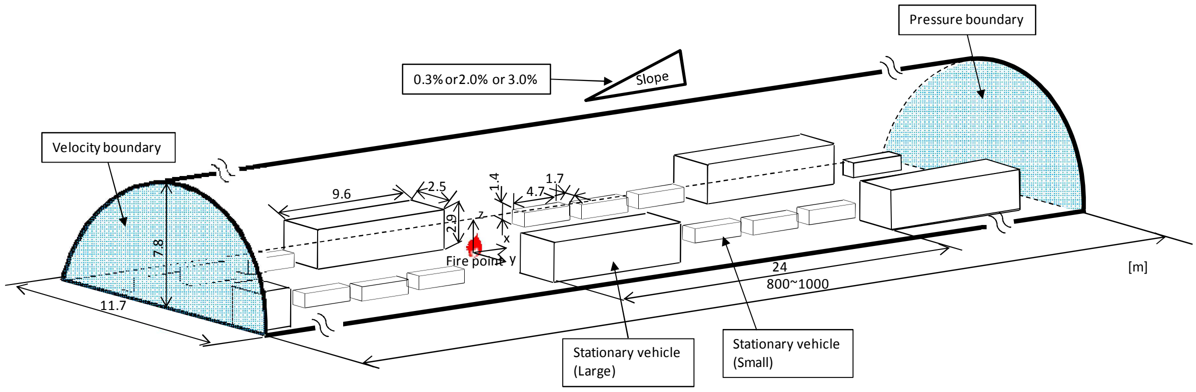


Figure 10 Ventilation simulation results at each fire point

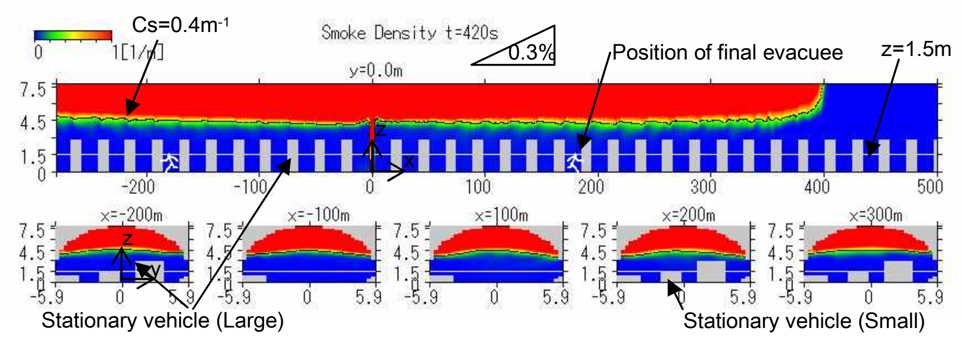
5. CHARACTERISTICS OF SMOKE BEHAVIOR IN THE YAMATOGAWA TUNNEL

5-1 Outline of 3-D Fire Simulation

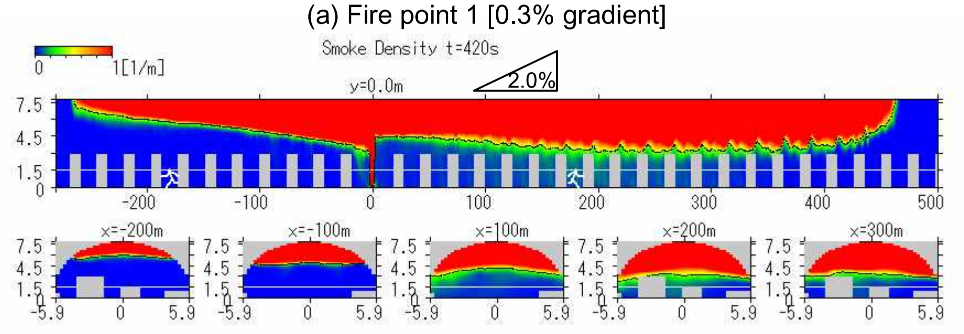
The prediction accuracy of the simulation code used in this study has been confirmed based on the comparisons with various full-scale tunnel fire tests. There are a lot of examination results regarding fire-safety in Japanese road tunnels using this simulator. Since the details of the numerical simulation method are described in a literature [6], only the outline will be explained here. Figure 11 shows an outline of the analytical area. The coordinate origin is the fire point, and the x-, y-, and z-axis represent the length, width, and height respectively. The grid size in the x-, y-, and z-direction is 0.4m, 0.35m, and 0.31m, respectively. A uniform distribution of velocity obtained by the 1-D ventilation simulation employed for the boundary condition of the upward portal (in negative direction of the x-axis). The free - flow condition (pressure p=0) was employed for the boundary condition of the downward portal (in positive direction of the x-axis). The analytical area was taken very long (800~1000m) in the direction of the x-axis, so that these boundary conditions should not influence the simulation results. Large-sized cars and small-sized cars as shown in Figure11 were arranged to consider the effects of the stationary vehicles in the congested-traffic condition.



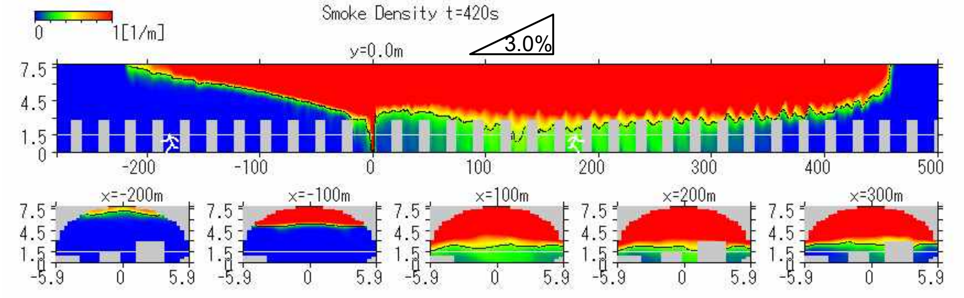
Pressure boundary
0.3% or 2.0% or 3.0%
Slope
Velocity boundary
9.6
2.5
1.4
1.7
4.7
2.9
7.8
Fire point
x
y
24
800~1000
11.7
[m]
Stationary vehicle
(Large)
Stationary vehicle
(Small)



(a) Fire point 1 [0.3% gradient]



(b) Fire point 2 [2.0% gradient]



(c) Fire point 3 [3.0% gradient]

Figure 12 Smoke density (Cs) distributions

5-2-2 Allowable Evacuation Distance

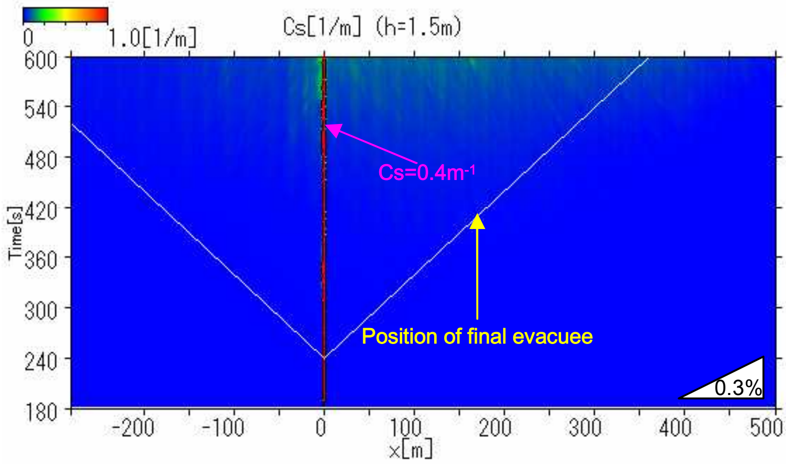
Figure13 shows how the smoke density (Cs) in the x-direction at a height of 1.5m is distributing as a function of time. The white solid lines indicate positions of the last evacuee as noted in the section 2-4 and the black solid lines indicate Cs=0.4 1/m in the illustrations.

Based on these results, the findings are summarized below.

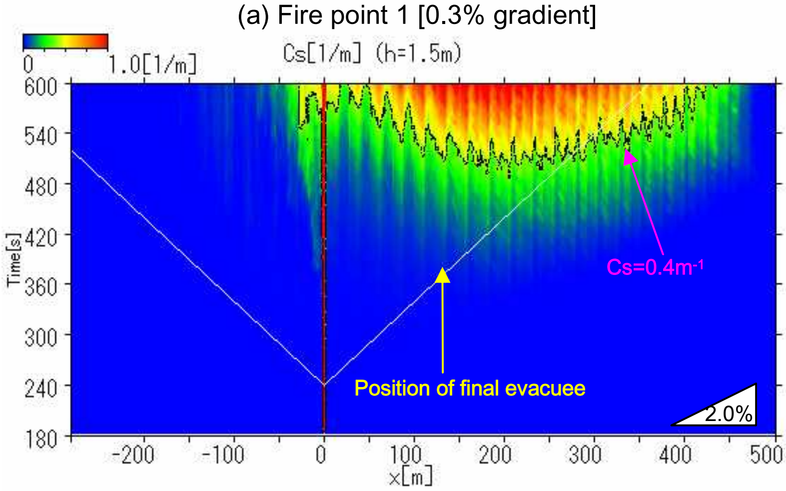
*In case of 0.3% gradient, there was free from smoke of Cs=0.4 1/m at a height of 1.5m, and the evacuation distance of over 300m was ensured.

*In case of 2% gradient, the smoke descent at a height of 1.5m was observed at approximately 480 seconds from the occurrence of the fire. The region of the smoke distribution was expanding as the time elapsed. The intersection position of the Cs=0.4 1/m line and the last evacuee's position line shows a distance which allows to evacuate safely. Hence, the allowable evacuation distance of approximately 280m was considered to be secured.

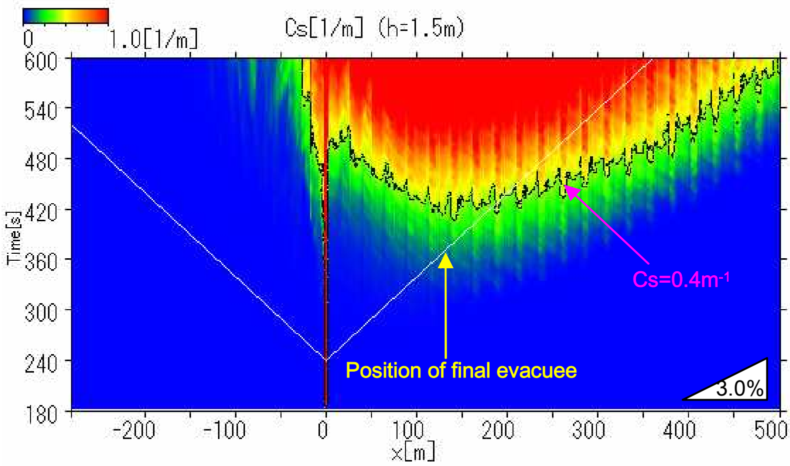
*In case of 3% gradient, the smoke descent began at approximately 400 seconds and the allowable evacuation distance was approximately 200m. Therefore, it was observed that as the gradients increased, the allowable evacuation distance became even shorter.



(a) Fire point 1 [0.3% gradient]



(b) Fire point 2 [2.0% gradient]



(c) Fire point 3 [3.0% gradient]

Figure 13 The smoke density (Cs) distributions in the x-direction at a height of 1.5m as a function of time

6. CONCLUSIONS

In this study, the smoke behavior during the emergency ventilation control in the Yamatogawa Tunnel was investigated. The findings are summarized below.

1. The longitudinal air-flow velocities were successfully lowered in the early stage of the tunnel fire. We confirmed that the de-stratification of the smoke and hot gases were prevented.

2. As the gradients of the road increased, the smoke layer developed thicker and the stationary vehicle influenced on the smoke diffusion.

3. As the gradients increased, the smoke descent began at earlier stage, and the allowable evacuation distance became shorter.

According to the results of this study, the allowable evacuation distances ware decided as Table 1 below.

Table1 Allowable evacuation distance for each tunnel gradient

Fire Point No.	Longitudinal gradient	Evacuation distance
1	0.3%	Within 300m
2	2.0%	Within 280m
3	3.0%	Within 200m

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